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Selection of U.S. Navy Ship alterations and improvements on the basis of efficient allocation of resources.

Riehl, Julian William

University of Maryland

SELECTION OF U.S. NAVY SHIP ALTERATIONS AND IMPROVEMENTS ON THE BASIS OF EFFICIENT ALLOCATION OF RESOURCES

by

Julian William Riehl, Jr.

Thesis submitted to the Faculty of the Graduate School
of the University of Maryland in partial fulfillment
of the requirements for the degree of
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ABSTRACT

Title of Thesis: Selection of U.S. Navy Ship Alterations and Improvements on the Basis of Efficient Allocation of Resources.

Julian W. Riehl, Jr., Master of Arts, 1968.

Thesis directed by: William A. Niskanen, Ph.D.
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This paper describes and exercises a five-step methodology designed to assist the military planner in solving the problem of selecting the most economically efficient U.S. Navy ship alteration or modification from among a group of proposed alternatives.

The model constructed pertains specifically to a single class of navy ship -- a hypothetical nuclear-powered submarine. The submarine is considered in a single mission category only, i.e., the destruction of enemy submarines while operating in an anti-submarine barrier. The general methodology, however, is designed to be applicable to other ship-types as well.

Four hypothetical, though representative, ship-alterations are selected for purposes of exercising the model.

The results of the problem are produced in the form of total systems cost vs. effectiveness and marginal cost vs. effectiveness curves. Data presented in this form provides the basis for selection of most economically efficient of the four alternatives under consideration.

Sensitivity-tests are conducted to determine the impact that variations in major parameters and assumptions will have on the problem results.

The methodology developed in this paper provides a method for selection of the most economically efficient alternative, but does not allow for the direct determination of an "optimum" solution point. This cannot be provided in this type of military benefit - cost analysis but must be determined by higher-level military and/or political considerations.

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CHAPTER I

INTRODUCTION

Among the many complex problems facing the military planner today is the persistent one that confronts the U.S. Navy in determining both the scope and detail of the Navy's continuing modernization and improvement program designed to maintain the vast U.S. fleet in a posture of maximum combat-readiness. Because of the technical complexity of the ship-board equipment systems and the long service life of 20 - 30 years of the ships themselves, major modifications to ships and their equipments tend to be expensive investments with long-term maintenance and operation cost implications.

In view of the considerable investment that the sum of such modifications will represent in the expected life-cycle of the ship, it becomes of critical importance that the decision to accept or reject each specific modification be undertaken within an analytical framework which provides a basis for selection based on the economically efficient principle of obtaining the desired military benefit with the minimum expenditure of input resources.

It is the design of this paper to apply systems analysis to the problem of obtaining the maximum military effectiveness for the total resources invested and, toward this end, to outline and test a general methodology that can be applied to the cost-effectiveness analysis of proposed U.S. Navy ship alterations. The term "alteration" hereafter will be used throughout the paper to describe any proposed modification or equipment change to an existing U.S. Navy ship that is designed to increase its military effectiveness.

The very immensity of the problem, with the wide variety of ships and mission assignments present in the modern navy, requires that the analysis be conducted at a fairly low level of sub-optimization in order to keep the dimensions of the analysis within manageable bounds. This paper, therefore, will address the problem of alterations which apply to a single specific type of ship. The methodology developed will be designed to have general application to other ship types and other specific mission assignments.

The basic conceptual approach followed is to consider the individual ship-system as analogous to a production process used by a firm to produce a specific product, its output. In the case of a man-of-war, the output or product is the ability of the ship to perform its assigned military mission. This is described by a specific measure-of-effectiveness, such as tons of ordnance delivered, area searched per unit of time, etc. In this context, then, the various proposed ship-alterations to be analyzed are analogous to alternative production processes available to a firm.

In the case of the firm, this problem can be approached by developing a so-called production function for each production process which relates output to units of factor inputs. With a cost relationship for the factor inputs, a production-cost function can next be derived which describes the total cost of producing the various levels of output. By comparing the production-cost curves of the various competing processes the most "efficient", i.e., least-cost system for a desired level of output can be determined. For selection of the "optimal" point, that which maximizes profit to the firm, however, marginal costs curves together with consumer demand curves must be examined, with the "optimal" point of profit maximization occurring at that production point where marginal cost is equal to marginal revenue.

In the case of our ship-alteration problem, the process of selection will be much the same, except that of necessity it must stop short of the final step of optimization. Optimization can generally not be accomplished in military systems analysis for two basic reasons:

(1) The military system lacks the market-mechanism for determining demand.

(2) Military systems output is almost always described in some term of measurement other than dollars. Since the optimization process of the firm is essentially that of maximizing the difference between the value of output (revenue) and costs, both dollar values, this step cannot be accomplished for military systems unless the output can be described in terms of dollar value, which generally is impossible.

Under these circumstances, the most meaningful result that a military analyst can accomplish is to present the production-cost relationship of each of the ship-alterations being considered in such a manner that the most "efficient" can be determined, either by examining which can produce the greater output for a given budget, or that which can produce a desired level of output for the least budget cost.

In this respect the systems analyst can be considered to be functioning much as the production manager of a firm might, in laying out and describing the various production-cost functions of the competing processes but leaving the decision as to the optimal operating point to be resolved by higher level management.

As mentioned earlier the complexity of the overall problem makes it necessary that a single type of ship be selected, around which to develop our analytical framework. The specific type selected for this study is the nuclear-powered attack-class submarine. This type and general class of ship was chosen for several reasons:

(1) It can be considered to have a single mission, predominant above all others, viz, the destruction of enemy submarines.

(2) It is a modern first-line ship with a large number and variety of proposed ship-alterations which represent various levels of resource costs, and which will provide a wide basis from which the alterations to be used in this study can be chosen.

With the selection of the specific ship-type to be used as the basis for our analysis, we can now summarize the general steps that our methodology will follow:

Step (1) Select the several representative ship-alterations to be used for comparison and analysis.

(2) Develop a production function which will express the relationship between numbers of submarines assigned to a mission (input factors) and their measured effectiveness in accomplishing that mission (output). Follow this procedure, developing a separate "production function" both for the basic submarine without alterations, and the basic submarine with the alterations added.

(3) Determine the total resource costs for each submarine configuration selected for analysis in Step (2), above.

(4) Develop Effectiveness vs. Total Cost and Effectiveness vs. Marginal Cost curves for each submarine configuration. These curves will provide the medium for comparison of the alternatives and will allow selection either on the basis of achieving maximum output for a given budget level, or the desired output for a minimum budget level.

(5) Repeat Steps (2) and (4), above, for a selected range of sensitivity tests varying the significant parameters and assumptions.

The following chapters will outline the above process in detail. Chapter II will develop the methodology, Chapter III the costing sub-model, and Chapter IV will analyze the results obtained from the testing of our model and implications of its value in further applications.

CHAPTER II

METHODOLOGY

Chapter One summarized a five-step outline of the methodology to be followed in conducting a systems analysis of the alterations to U.S. Navy ships, specifically, nuclear-powered submarines. These five-steps are:

1. Select the ship alterations for comparison
2. Develop a production function
3. Determine costs
4. Develop Effectiveness vs. Cost curves
5. Conduct sensitivity tests.

Before proceeding further in development of the methodology, it will be prudent to check the completeness of our proposed procedure by comparison with more formalized definitions that have been established for the analytic process that we propose to use.

The textbook definition of the systems analysis procedure contains five essential elements which are common to any problem involving choice among alternative weapons systems. These elements have been described by E. S. Quade as follows:

> "1. The objective. Systems analysis is undertaken primarily to suggest or, at the very least, help to choose a course of action. The action must have an aim or objective. Policies or strategies, forces or equipment are examined, compared, and preferred on the basis of how well and how cheaply they can accomplish the aim or objective.

2. The alternatives. The alternatives are the means by which it is hoped the objectives can be obtained. They need not be obvious substitutes or perform the same specific function.

3. The costs. Each alternative means of accomplishing the objectives implies the use of specific resources which cannot be used for other purposes.

4. A model (or models). The model is a representation of the situation under study designed to predict the cost and performance of each alternative. It abstracts the relevant features of the situation by means which may vary from a set of mathematical equations or a computer program to an idealized description of the situation in which judgement alone is used to assess the consequences of various choices.

5. A criterion. A criterion is a rule or test by which one alternative can be chosen in preference to another. It provides a means for using cost and effectiveness to order the alternatives."[1]

A careful inspection of our five-step methodology outlined in Chapter One will reveal that each of the above essential elements is contained within its framework:

The objective - This is the mission of the nuclear-powered submarine as stated in Chapter One; i.e., the destruction of enemy submarines. It must be more precisely defined in terms of a specific measure of effectiveness. This will be accomplished later in this chapter.

The alternatives - These are the various ship-alterations which have been selected for analysis. They will be described in detail in this chapter.

The costs - The role of costs in our methodology has already been discussed in Chapter One. The costing sub-model is covered in Chapter Three.

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[1]E. S. Quade, (ed.), Analysis for Military Decisions (Chicago: Rand McNally and Co., 1964), p. 155.

A model - In essence the whole five-step procedure for the methodology presented in Chapter One, is in fact an outline of the model by which the analysis will take place.

A criterion - The criterion for choice is provided by Effectiveness vs. Total Cost and Effectiveness vs. Marginal Cost curves, which provide the basis for selection from among the alternatives by the higher-level decision-maker.

Having determined that our basic methodology appears complete in its essential elements let us now examine the inner-structure of each procedural step in greater detail.

The Production Function.

Since our "production function" is a relation between numbers of submarines and effectiveness of these submarines, it is essential that some measure-of-effectiveness be derived that will adequately gauge the level of performance of the submarine in the accomplishment of its mission. The measure of effectiveness (MOE) should fulfill several requirements:[1]

(1) It must be relevant to the mission of the system being considered.

(2) It should be measurable.

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[1]William A. Niskanen, U.S. National Security Objectives and the Choice of Measures of Effectiveness (Internal Note N-301(R), Economic and Political Studies Division, Institute for Defense Analyses, Arlington, Va., 1965), p. 4.

The MOE selected that fulfills both of these requirements is the probability of killing an enemy submarine (PK). This MOE is obviously related to the basic mission being considered, the destruction of enemy submarines; and, as we shall see, it is a measurable quantity in that it is the measure of output used by our tactical sub-model in generating our production (effectiveness) function.

Since the Probability of Kill is probabilistic in nature, it has the added advantage of being applicable to any size enemy force and hence tends to broaden the range of applicability of our results.

Having selected our basic system, the submarine, and determined its mission and the relevant MOE, the next step is to describe the mission environment within which the submarine will operate. There are various methods that a submarine can follow in seeking out and destroying another submarine. This paper will investigate but one of these; the remainder must be the subject of separate analyses. The method of operation selected for this analysis is one in which U.S. submarines form in a single line or "barrier" across the expected path of enemy submarines. The concept of this type of operation is that the submarines forming the barrier will lie quietly in wait and attack the enemy submarine as he passes through the area in which the barrier has been established.

In order to generate our production, or effectiveness, function we will require a tactical sub-model which can satisfactorily represent the tactical situation that we desire and which is capable of generating the desired measure of effectiveness, Probability of Kill (PK), over a broad range of variable input parameters.

This type of result could be obtained by several types of models. One type is an analytical model which describes the relationships in mathematical terms from which the end result (PK) can be calculated. Because of the complex relationships that exist both with respect to the geometrical configurations that develop in the course of an attack problem, and the description of basic physical phenomena involved, such as the propogation of sound-waves in an open-ocean environment, such a model has yet to be developed in a satisfactory form. This writer was unfortunately unable to advance the state of the art to any significant extent.

The second type of model is one that solves the attack problem by means of a computer simulation. A great deal of progress has recently been made in this area, with a number of models currently under development. One such working computer model that proved adaptable to the requirements of this study is the "CNA-Sub vs. Sub Model" developed by the Center for Naval Analysis. This model was employed in our analysis to develop the basic effectiveness function for each of the submarine configurations studied. Specific advantages presented by this model were that it satisfactorily approximated the dynamics of the tactical situation, and allowed for a full range of variation of the significant parameters, such as equipment and performance characteristics of both U.S. and enemy submarines, sound propogation conditions, and adjustment of barrier geometry.

It should be noted that the ability of such a model to recreate the real world of the tactical engagement is extremely critical to the usefulness of the results obtained and must be carefully examined in any analysis upon which actual decisions are to be based. Since the purpose of this paper is to develop a methodology and not to produce results that are accurate in any absolute sense, any tactical submodel which results in a rough approximation of the real world would be entirely satisfactory for the stated objectives of this study.

In order to generate the basic production function relating effectiveness to the force level of submarines, a number of limiting conditions must be applied to our tactical sub-model:

(1) The dimensions of the submarine barrier must be established and will be held constant throughout the problem. The size of this barrier will be dictated by the specific wartime mission, the specific force level and range of effectiveness desired to be tested.

(2) The environmental conditions must be specified. The sound propogation conditions and sea state are especially critical since they affect the distances at which the submarines can detect each other. These inputs are considered to be parameters and will be varied during the process of sensitivity testing.

(3) The performance characteristics of both the barrier submarine and the enemy submarine must be specified. To avoid entering into areas of security classification the characteristics used were purposely chosen to avoid representation of any specific class of ship. The exact characteristics used must of course remain classified, but further discussion, in general terms, is included in Chapter Four.

(4) In order to present a standard tactical problem, it is assumed that the enemy submarine would transit the barrier at right angles to the barrier itself, and would transit at a steady speed until an actual engagement takes place. The various tactical assumptions regarding the actions that each submarine would undertake during the engagement phase are classified information. It is further assumed that enemy submarines will transit singly and will arrive at the barrier at random intervals in time and with a uniform frequency distribution.

With the dimensions of the barrier established and the input variables selected, the actual effectiveness vs. force level data can now be generated by placing varying numbers of U.S. submarines, equally spaced, within the barrier confines and exercising the computer sub-model to obtain a probability-of-kill on a random transiting enemy submarine, for each number of U.S. submarines placed in the barrier.

The resulting data will be used to generate our desired production function in terms of effectiveness (PK) vs. numbers of U.S. submarines used to form the barrier. Representative curves of this type are shown in Figure 4-2. These curves have been produced for each of the four submarine configurations selected for testing as alternative systems. Each of these alternative choices is discussed in the following section.

Selection of Alternatives to be Compared.

A wide variety and number of prospective submarine alterations were available from which to choose the four alternatives used in our model. The alterations actually selected were chosen on the basis of their expected impact on the output function, their applicability to the submarine mission being analyzed, and to produce as wide a variation as possible in exercising the costing sub-model.

Actual values pertaining to the performance and cost data of each alteration are classified, so exact figures cannot be presented. Comparisons will be made on a relative basis only.

The four basic alternative ship configurations selected for comparison and testing in the model are as follows:

Alternative (1): A basic (hypothetical) nuclear-powered submarine. Specific performance characteristics were assigned to this submarine such as speed, radiated and self-noise, and the underwater detection ability of its sonar equipment. The characteristics of a torpedo weapon system were also provided.

Alternative (2): The basic submarine described as Alternative (1), above, plus a significant improvement to the passive sonar equipment which increases the expected detection range on the enemy submarine.

Alternative (3): The basic submarine plus new equipment and technical refinements which improve both the self-noise and radiated-noise characteristics of the submarine. Improved (lower) self-noise will increase the submarines ability to detect the enemy submarine, and lower radiated-noise will reduce the range at which the submarine, itself, can be detected by the enemy.

Alternative (4): The basic submarine plus an improved weapons system which includes an advanced type of torpedo of increased range and speed.

The above alternatives will produce a fairly wide range of effects on the performance characteristics of the basic submarine. In addition, they represent a wide variation in types and amount of costs incurred; e.g., alternative(2) has moderate installation costs with research and development costs already expended; alternative (3) had moderate research and development costs not yet expended plus high investment and increased maintenance and operation costs. Alternative (4) is by far the most expensive -- with high research and development costs plus high investment and continuing maintenance costs.

The cost sub-model used for each of these alterations is discussed in detail in Chapter Three.

Criterion for Comparison.

As described earlier, in Chapter One, the concept of our methodological approach is to develop an analytical framework which will produce a basis for comparison similar to that followed by the individual firm in selecting from among several competing production processes. That basis for comparison, in the context of our study, is the Total Cost vs. Effectiveness curves and Marginal Cost vs. Effectiveness curves developed by combining the production function, above, with the costing data generated in Chapter Three.

As explained earlier, our analysis must of necessity stop short of choosing an "optimal" solution since it is meaningless to attempt to maximize the difference between effectiveness, measured in PK, and the resource costs, measured in dollars. With this limitation, the best our analysis can do, is to select the most efficient of the four alternative ship configurations presented for comparison. There are two specific criteria that may be applied in this instance: either -- that alternative which produces the maximum effectiveness for a given budget, or -- that alternative which produces a given level of effectiveness for the least budget. Either of these criteria can be applied directly to the Total Cost vs. Effectiveness curves and selection of the most efficient system made on the basis of the budget-level or effectiveness constraints imposed by the decision-maker.

The marginal cost curves display the relation of increment of total cost per increment of effectiveness as the level of effectiveness is varied. This information is not directly helpful in making our basic selection of the most efficient alternative but, as we shall see, can be of aid in determining the most efficient -- "cost-effective" -- area for operation of the selected system, and can be used as a basis for comparing effectiveness with other military units performing the same mission.

The total cost and marginal cost curves developed as a result of this study are shown as Figures 4-3 through 4-9. The specific results of applying the criterion to these curves are discussed in Chapter Four.

Sensitivity Testing

Once the basic set of cost-effectiveness curves has been generated, the results must be tested to determine their sensitivity to variations in significant input parameters.

This is accomplished by re-running the basic problem for each of the alternative submarine configurations with the new values of input parameters inserted. The results are then compared to determine their sensitiveness to the parameters that were varied.

It is apparent that an almost limitless number of combinations of parameter variations are available for testing. In view of the time constraints on the analyst, only a few of the apparently significant parameters were varied in this analysis and primarily to develop limiting cases.

Sensitivity tests, using in each instance variations from the basic problem conditions, were conducted in the following cases:

(1) Variation of sound propagation conditions

(2) Variation of enemy submarine characteristics

(3) Variation of the location of the submarine barrier from home port.

The results and significance of these tests are discussed in Chapter Four.

CHAPTER III

COST ANALYSIS

In systems analysis we are concerned with the problem of minimizing the consumption of scarce resources for a fixed or desired level of output, or maximizing the output with respect to a given level of resource consumption. In military systems analysis dollar cost is used as an approximation of the real cost of the total resources expended. For example, in the four alternative systems that we have under consideration in our present problem, we need some way of representing the sum of the many dissimilar resources involved: Training, equipment, hardware, torpedoes, manpower, base facilities, tender support, etc. The single measure that can be applied to all, and hence to the aggregation of the resources, is dollar cost.

The computation of the total dollar cost is obviously of critical importance to the results of any cost-effectiveness type analysis. As pointed out by G. H. Fisher,[1] it is not necessary that the cost estimates produced be precisely accurate to the degree required for budget administration, but they should be as accurate and inclusive as possible in the relative sense -- for the comparison of competing systems. Toward this end consistent

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[1] Quade, op. cit., p. 266.

rules for the inclusion and aggregation of costs must be applied to all systems being compared.

There are three primary problem areas for which rules must first be established in order that our cost analysis proceed on a consistent basis:

(a) Selection of a planning period

(b) Estimation of the value of resources at the beginning and end of the planning period, and

(c) Selection of the rate of interest for present value computations.

Selection of the Planning Period.

The planning period provides the basic time framework within which the total investment and operating costs are aggregated for each system. The length of the planning period is largely dependent on the average service life of the military system being considered. In this study we have a basic nuclear submarine system with an expected service life of from twenty to thirty years. In addition, we have several proposed alterations to this basic submarine system, each of which will have a service life considerably less than that of the basic submarine. A ten-year service life was assumed to be an average figure for these types of alterations which would normally be expected to be replaced two or three times during the total life span of the ship, itself. Since the main effort of our analysis will be in inter-comparisons of the proposed alterations, the logical choice for the planning period is the length of average life-cycle of the alterations, or ten years. This result also corresponds with a standard rule prescribed for military analysis.[1]

With the length of the planning period established, the next step is to determine at what point in the future the planning period should begin. The beginning point of the planning period will be determined by the date furthest in the future that any of the systems under consideration will be ready for active operational service.

In this instance, our systems all have different planned research and development phases. The new torpedo system has a five-year development plan, of which two years have already been completed; the sonar improvement alteration has a three-year development plan which can commence immediately; the sound characteristics alteration has completed its research and development phase and can be placed in service in the current fiscal year.

Following our rule that the latest system to become operational will determine the beginning point of the planning period -- the first year of our planning period will be four years hence, or fiscal year 1971.

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[1]William A. Niskanen, A Suggested Treatment of Time-Distributed Expenditures in Defense Systems Analysis (Internal Note N-396(R) Economic and Political Studies Division, Institute for Defense Analyses, Arlington, Virginia, 1966), p. 6.

Estimated Value at Beginning and End of the Planning Period.

In arriving at the estimated value to be assigned each system at the beginning and end of the planning period, several different circumstances present themselves.

In the case of the sonar improvement alteration and the noise characteristics improvement alteration the useful military life of each alteration is considered to be ended at the completion of the ten-year planning cycle. The value for this end position is calculated using the rule of exponential decay of value which results in a value at the end of the ten year service life equal to 25 percent of the original investment cost.[1]

For the new torpedo system it was assumed that at the end of ten years the torpedo would either be retained for use with older submarines or would be sold to foreign governments at about 50 percent of the original investment value.

In the case of the basic submarine configuration neither an investment value at the beginning of the planning period nor a salvage value at the end was computed. This is justified on the grounds that the original investment is considered "sunk" since all the submarines in our hypothetical force are assumed to already have been built at the start of our problem. The salvage value at the end of the planning period is not included for two reasons:

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[1] *Ibid.*, p. 9.

(1) Based on a twenty year service life the salvage value figured by the exponential-decay rule would be 50 percent of the original investment value. Because of the extremely high value of original investment this would seriously distort the total cost value computed for the submarine.

(2) Since the total cost of the basic submarine is also included in the total cost of each of the alterations being computed the salvage value of the basic submarine would be common to all of the systems costs and can therefore be eliminated without serious consequences.

Selection of Interest Rate for Present Value.

In constructing our cost-analysis sub-model we employ the principle of "discounting" the value of future expenditures in terms of some selected discount rate. To explain the relevancy of this concept we refer back to the analogy of the production firm that we introduced in the first chapter. This firm in its financial operations has an option of investing the funds it has available today at the going market interest rate. If this rate of return is six percent per year then $100 in hand, today, is the equivalent of $106 a year from now and, assuming the rate of return holds constant, should be worth about $180 ten years from now. In making its investment decisions, therefore, the firm must consider, among other things, not only the expected rate-of-returns but the future time-period in which the investment (costs) will take place. One method used to make costs (and benefits) occurring at different future times equivalent, is to apply an appropriate discount rate to all future values, so that all are stated in terms of "present value" of the dollar.

The value of a dollar in some future year (t) in terms of a present dollar is related to some specified interest rate (r) in the following way:

$$P_t = \frac{1}{(1+r)^t}$$

where:

P_t = Value of dollar at some future year, t.

r = appropriate interest rate.

In the comparisons of alternative military systems, the reasons for discounting are precisely the same as they are for the private firm. The $180 gain (cost) that will occur ten years from now is the equivalent of only $100 today because resources can be made to grow that much if put to alternative uses (assuming a constant interest rate of 6 percent in the future).

For example, a ship-alteration that requires heavy expenditures immediately uses funds, today, which could have been used to finance productive private investment. In considering the total future costs allowable to this alteration, therefore, it should be charged at least a rate representing the market's evaluation of the marginal productivity of such investment.[1]

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[1]Charles J. Hitch and Roland N. McKean, The Economics of Defense in the Nuclear Age (New York: Antheneum, 1966), p. 206.

For this reason any aggregation of the expenditures for a military system over a period of years implies the use of some interest rate to reduce the value of these expenditures in terms of today's dollar. Failure to do so will result in a bias in cost analysis in favor of those systems with a shorter life-cycle, or those for which the bulk of expenditures occur early in the life-cycle.

The interest rate chosen for present-value computations in this paper is ten percent. This represents the opportunity costs to the government of government borrowing activity and is higher than merely the going interest rate on government bonds.[1] The government bond interest rate should be adjusted by subtracting additional personal income taxes realized on the interest payments and adding the corporate and personal income taxes lost through reduction in capital formation.

The components of this ten percent which represents the total borrowing cost to the government have been computed as follows:[2]

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[1] The rationale underlying this selection is presented in further detail in William A. Niskanen, A Suggested Treatment of Time-Distributed Expenditures in Defense Systems Analysis, pp. 13-17.

[2] Ibid., p. 17.

Government Borrowing Rate	+ 4.7%
Less Personal Income Tax on Interest	- 1.6%
Plus Corporate Taxes Forgone	+ 4.6%
Personal Income Taxes Forgone	+ 2.0%
	9.7% $\cong$ 10%

The above system of computation is considered valid under the general current economic situation in the United States where the economy is at a level of full or nearly-full employment with total private investment at a constant level, in the short term. Under these circumstances, a dollar of government borrowing can be assumed to displace a dollar of private investment.

Categories of Costs.

The components of each system cost were considered in three time-phased categories:

(a) Research and development costs. These are considered to be fixed-costs and independent of the force level.

(b) Investment costs. These expenditures are a function of the force level but are essentially one-time costs. These costs include the original equipment and installation costs plus the cost of constructing supporting installations which are pro-rated over the force of submarines.

(c) Operating costs. Expenditures which are a function of the force level and which are recurring in nature. These include pay and allowances, maintenance and operation expenditures.

The formula by which the future time-stream of system costs can be collapsed into a present value is:

$$PV = \sum_{t=o}^{n} \frac{C_t}{(1+r)^t} , \quad \text{where } (n+1) = \text{number of years}$$

until the end of the planning cycle; C_t = the cost in the t_{th} year; r = interest rate at which future costs are discounted; PV = present value of future expenditures.

Costing Procedures for Individual Systems.

Tables 3-1 through 3-4 display the samples of the cost-stream summary formats used in the computation of the aggregate discounted system costs for each of the submarine configurations being analyzed. Since the cost data is classified, actual dollar values do not appear in these examples. A discussion of the major cost components of each configuration's system costs plus supporting rationale is included below.

Basic Submarine System Costs (Table 3-1). No research and development or investment costs appear in this format. Since the entire force of submarines being considered is assumed to be already in existence, these costs are treated as "sunk" costs. The system costs considered therefore consist entirely of recurring operating and maintenance costs for the ten year planning period extending from fiscal year 1971 through 1980. Actual cost data used were average figures of several classes of submarines obtained from the Navy Program Factors Book, OPNAV 90P-02.

TABLE 3-1

BASIC SUBMARINE SYSTEM COST-STREAM SUMMARY

Fiscal Year	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980
Discount Year (t)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
<u>Operation & Maintenance</u> (Pro-rated)										
Non-Scheduled Repairs	xxx									
Personnel Pay & Allowances	xxx									
Maintenance Material	xxx									
Supply & Equippage	xxx									
Alterations	xxx									
Indirect Support	xxx									
Total O & M Costs	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX
Overhaul				xxxx			xxxx			xxxx
Nuclear Core										xxxx
Total Annual Pro-Rated Costs	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX

<u>Non-scheduled Repairs</u>: The average value of annual voyage repairs needed to keep submarines in first-line operating condition.

<u>Personnel Pay and Allowances</u>: Self-explanatory.

<u>Maintenance Material</u>: Annual expenditure for major items of equipment requiring replacement.

<u>Supply and Equippage</u>: Annual cost of replacement spare parts and consumables, plus some major items of equipment not included above.

<u>Alterations</u>: Average annual cost of major modifications which are required to maintain or improve military capability.

<u>Indirect-Support</u>: A pro-rated portion of the overall navy support cost for training, logistics, and overhead, which can be considered to be a function of the number of ships in the active fleet.

<u>Overhaul</u>: Total charges incurred for an average overhaul. The overhaul cycle for our hypothetical submarine is assumed to be 6 months of overhaul and 36 months of operation.

<u>Nuclear Core</u>: Nuclear core replacement will occur at approximately regular intervals. The exact interval used for planning is classified. It is assumed to be greater than ten years, and the cost figure appearing in the last column (FY 80) is adjusted by an appropriate factor, less than 1.

<u>Total Cost Function</u>: Each of the cost components is a function of the number of submarines, therefore the formula for the thirteen-year discounted total system cost of the basic

submarine configuration is:

$$\text{Total Cost} = PV\ (S)$$

where:

PV is the present value of the discounted cost-stream computed by $PV = \sum_{t=3}^{12} \frac{C_t}{(1+r)^t}$;

C_t = Total systems cost for year "t".

S is the number of submarines being considered.

Improved Torpedo Weapon System Costs (Table 3-2). For the sake of illustration, it is assumed that the improved torpedo and its associated weapons system is one that has a five-year research and development schedule, of which two years have already been completed. This system presents an interesting exercise in cost analysis since it includes examples of all categories of costs that have been discussed including research and development costs, one-time investment and support costs, and salvage values for both the current and the future torpedo systems.

Research and Development, Test and Evaluation: This item includes all costs associated with the research and development, test and evaluation of the torpedo. This is a fixed cost considered independent of the number of torpedoes which are produced.

Investment - Weapons System: This includes the initial allowance of torpedoes carried on board the submarine plus an additional amount carried in supply stock-points as reserve for

TABLE 3-2

IMPROVED TORPEDO WEAPON SYSTEM COST-STREAM SUMMARY

Fiscal Year	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980
Discount Year (t)	(0)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Research & Development	xxxx	xxx	xxx										
Test & Evaluation		xxx	xxx										
Total Fixed Costs	XXXX	XXXX	XXXX										
<u>Investment</u> (Pro-Rated)													
Weapons System				xxxx									
Base & Tender Support	xxx	xxx	xx										
<u>Operation & Maintenance</u> (Pro-rated)													
Torpedoes Expended				xxxx	xxxx	xxxx	xxxx	xxxx	xxxx	xxxx	xxxx	xxxx	xxxx
Training & Maintenance				xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx
Spares				xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
Salvage Value (MK 37)				(-)xxxx									
Salvage Value of Improved Torpedo System													(-)xxxx
Total Annual Pro-rated Costs	XXX	XXXX	XX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX

each submarine. Also included are the equipment and installation costs of the associated ~~fire~~-control system and the initial buy of spare parts for both torpedoes and the fire control system.

Investment - Support: This includes the costs of modifying submarine tenders and shore-based facilities required to support the new weapons system. The figure used was arrived at by computing the support cost for the total force of submarines being considered and dividing by the number of submarines to obtain an average, pro-rated figure.

Operating Costs - Torpedoes Expended: This figure is the total cost of the number of torpedoes planned to be fired by each submarine in peace-time exercises each year times a factor to account for the average torpedo loss-rate.

Operating Costs - Training and Maintenance: The total costs of the additional maintenance and training support personnel required by the new weapons system. This total cost figure is divided by the total number of submarines to obtain an average pro-rated figure.

Operating Costs - Maintenance Spares: Estimated cost of annual incremental consumption of spare parts required to refurbish torpedoes fired in exercises each year by each submarine. This figure is computed by subtracting the average spare parts cost of the old torpedo from the estimated costs of the new torpedo.

Salvage Value of the Present Weapons System (Mk 37 Torpedo): This figure represents the value of the present weapons system in its alternative uses. Two alternative uses are possible, the torpedoes may be retained for use on older second-line submarines or they may be sold to foreign navies. It was assumed that 50 percent were retained and that 50 percent were sold at some fraction of their cost of replacement. The salvage value used is the average of these two prices multiplied by the total number of torpedoes carried on board and in reserve for each submarine. This Mk 37 salvage figure is subtracted from the investment figure for the new weapons system.

Salvage Value of the New Weapons System: This figure is computed in the same manner as for the Mk 37 weapon system, described above. The total value for each submarine is then entered as a minus quantity in the last year (FY 80) cost column.

Total Cost Function: The total cost function for the improved torpedo weapons system is represented by the following formula, expressed in terms of thirteen-year discounted costs:

$$\text{Total Cost} = TC_B + PV_1 + PV_2(S)$$

TC_B = Total cost of the basic submarine as computed on page 28.

PV_1 = Present value of R&D costs computed by:

$$PV_1 = \sum_{t=o}^{2} \frac{C_t}{(1+r)^t} \quad ; \; C_t = \text{R\&D costs}$$

for year "t".

PV_2 = Present Value of Investment and Operating costs computed by: $PV_2 = \sum_{t=3}^{12} \frac{C_t}{(1+r)^t}$;

C_t = Investment and operating costs for year "t".

S = Number of submarines.

Sonar Improvement System Costs (Table 3-3). The sonar improvement alteration has a projected research and development period of three years. On the basis of engineering estimates it is assumed that the addition of the alteration will cause no significant increase in maintenance or support requirements over those of the presently installed sonar equipment.

Other line items of Table 3-3 are for the most part self-explanatory.

Since the alteration is essentially a modification of the present sonar equipment, no salvage value can be attributed to the old equipment, as it remains in use. The salvage value of the sonar improvement alteration at the end of the ten year life-cycle is calculated at 25 percent of its original investment cost, using the exponential-decay rule for value depreciation of military equipment.

The derived total cost function for the sonar improvement configuration expressed in terms of a thirteen-year discounted cost is:

$$\text{Total Cost} = TC_B + PV_1 + PV_2(S)$$

where:

TC_B is the total cost of the basic submarine computed as on page 28.

PV_1 is the present value of R&D costs.

PV_2 is the present value of operation and maintenance costs.

PV_1 and PV_2 are computed in the same manner as shown for the torpedo weapons system on page 31.

S = Number of submarines.

Noise Improvement Systems Costs (Table 3-4). All research and development work is assumed to have been completed on this alteration. These costs therefore represent non-chargeable, "sunk," expenditures. Maintenance costs for the new and modified equipments are considered to be no greater than for the equipment that it replaces.

Trials: This is a recurring item that refers to special trial runs conducted by the submarine to test its sound noise characteristics. It is estimated, for the purposes of this study, that these will occur at the time of each overhaul period.

Training and Facilities: These items represent the costs of additional training personnel and new facilities required to support this alteration. The figures are in terms of the pro-rated value of the total cost for each submarine.

Salvage Values: Presently installed equipment is assumed to have no salvage value since a large proportion of it is modified and retained as part of the new alteration and the remainder has value primarily as scrap. The end point salvage value for the newly installed equipment is computed at 25 percent of the initial investment cost, using the exponential decay-rate principle.

TABLE 3-3

SONAR IMPROVEMENT SYSTEMS COST-STREAM SUMMARY

Fiscal Year	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980
Discount Year (t)	(0)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Research & Development	xxxx	xxxx	xxxx										
Total Fixed Costs	XXXX	XXXX	XXXX										
Investment (Pro-rated costs)													
Equipment				xxxx									
Installation				xxx									
Salvage Value of the New System													(-)xxxx
Total Pro-rated Annual Costs				XXXX									(-)XXXX

Cost Function: The total cost function for the noise improvement alteration, expressed in terms of thirteen year discounted costs is:

$$\text{Total Cost} = TC_B + PV(S)$$

where:

TC_B is the total cost of the basic submarine derived on page 28.

PV = Present Value of Operation and Maintenance Costs computed as for the basic submarine on page 28.

S = Number of Submarines.

TABLE 3-4

NOISE IMPROVEMENT SYSTEM-COST STREAM SUMMARY

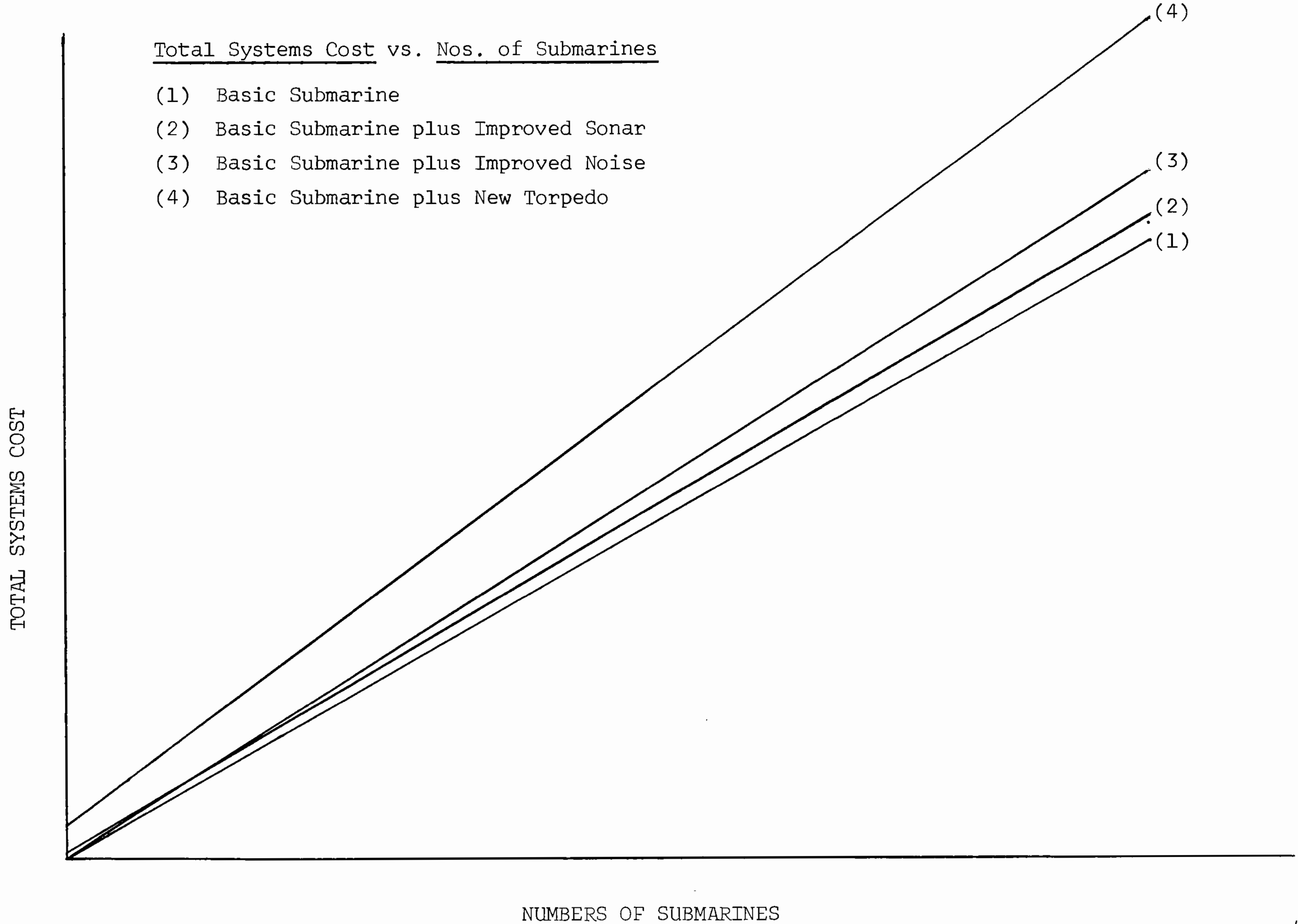
Fiscal Year	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980
Discount Year (t)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
<u>Investment</u> (Pro-Rated)										
Equipment	xxx									
Installation	xxx									
Design	xx									
Facilities	xx									
<u>Operation & Maintenance</u> (Pro-Rated)										
Training (Personnel)	x	x	x	x	x	x	x	x	x	x
Trials	xxx				xxx				xxx	
Salvage Value of New System										(-)xx
Total Annual Pro-Rated Costs	XXXX	X	X	X	XXX	X	X	X	XXX	(-)XX

Summary.

In summary, we have compiled in this chapter the total system cost applicable to each of the four basic submarine configurations, or systems, that we have under consideration. We have further derived a total cost function for each system which relates the total resource costs of each system to the submarine force level for a thirteen year cost period, discounted at a standard rate of ten percent per year.

A plot of these four total cost functions vs. the force level of submarines is shown in Figure 3-1.

In Chapter Four these relationships will be combined with the effectiveness function to produce effectiveness vs. cost relationships which serve as the basis for the comparison of our alternative systems.



Total Systems Cost vs. Nos. of Submarines
(1) Basic Submarine
(2) Basic Submarine plus Improved Sonar
(3) Basic Submarine plus Improved Noise
(4) Basic Submarine plus New Torpedo
(4)
(3)
(2)
(1)
TOTAL SYSTEMS COST
NUMBERS OF SUBMARINES

FIGURE 3-1

CHAPTER IV

TESTING AND COMPARISON

In this chapter we shall exercise and test the methodology that we have constructed in the previous chapters. We shall do this by outlining the precise circumstances under which the problem is assumed to be conducted, by supplying the required input data in consonance with our basic limiting conditions, developing our basis for comparison -- the cost-effectiveness relationships, and applying our criterion for selection. We shall examine the results produced by our methodology and conduct several tests to determine the sensitivity of our results.

As a preliminary step to the actual exercise of our methodology, the basic conditions under which our problem is to be conducted must be clearly established. These conditions can be broken-down into the following elements:

(1) A summary of the general assumptions under which our model was developed.

(2) A description of the military mission.

(3) A description of environmental conditions.

(4) A description of the U.S. submarine characteristics.

(5) An estimate of the enemy submarine characteristics.

(6) A statement of the pertinent tactical assumptions.

General Assumptions.

(a) Our analysis is conducted on the level of sub-optimization which assumes that there is no question as to the validity of the submarine mission of destroying enemy submarines, i.e., we are not concerned with the comparison of other competing military systems, such as destroyers, aircraft, etc.

(b) It is assumed that the entire force of submarines concerned in this problem is homogeneous in nature; it consists of a single type and class of ship -- a hypothetical nuclear attack-class submarine, with a single primary military mission. That mission is the destruction of enemy submarines. It is further assumed that in carrying out this mission, the submarines will operate in an anti-submarine type barrier.

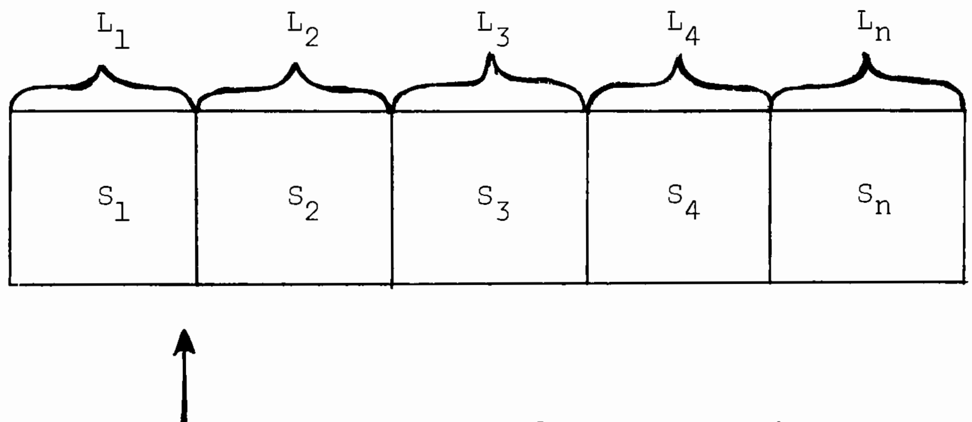
(c) It is assumed that the enemy submarine force is also homogenous in nature, and all the enemy submarines follow the same tactics in approaching and traveling through the barrier area.

(d) The problem is conducted under the general strategic conditions of limited or general, non-nuclear war.

Description of the Military Mission.

A single type of mission is assumed, specifically, one in which the U.S. submarines form a "barrier" and lie in wait for the enemy submarine. For the purposes of our problem, a rectangular-shaped barrier is formed with each submarine assigned an equal area of responsibility within the barrier. The barrier is placed at right angles to the expected path of enemy submarines, and consists of only a single line-abreast formation of submarines.

A schematic representation of such a barrier is shown in Figure 4-1 below:



Direction of approach of enemy submarines.

FIGURE 4-1

where:

$S_1, S_2, \ldots S_n$ represents the area assigned to each submarine in the barrier

$L_1, L_2, \ldots L_n$ is the distance measured along the front of the barrier for each submarine area.

$$L_1 = L_2 = L_3 \;\ldots\ldots\; = L_n.$$

The dimensions of this barrier must be specified. Its size directly controls the scale of the problem since the length of the barrier determines both the force level of submarines required to support the barrier and range of effectiveness levels that can be produced by the problem.

Environmental Conditions.

A standard set of environmental conditions are assumed for our basic problem. These include characteristics of the ocean area in which the barrier has been established: Water temperature, salinity, density, depth of water, sea-bottom conditions, the variation of temperature and density with depth of water and sea-state (a roughness measure of the surface of the water). From this data is developed a mathematical expression relating the propagation of sound in the water to distance, for the particular area considered. This is based on methods described in Commander of Submarine Development Group Two, Sonar Operators Manual. The exact conditions selected cannot be described, here, but will be termed as "average" for our basic problem set.

For our basic problem, also, it is assumed that the barrier is situated immediately adjacent to the port at which the U.S. (barrier) submarines are based. This is significant in that it means that no time is lost by the submarines in traveling from the home port to the barrier location.

U.S. (Barrier) Submarine Characteristics.

The performance characteristics of the barrier submarines for each of four alternative submarine configurations are established for the following items: Speed capability, radiated noise vs. speed; self-noise vs. speed; characteristics of the underwater sensor system (the sonar) described in technical measurements of "recognition differential" and "directivity index"; and characteristics of the torpedo weapons system including speed, range, and variation of torpedo probability-of-kill with range. The variation of error in the solution of the tactical problem by the barrier submarine as a function of the range of the enemy submarine is also provided.

The Enemy Submarine Characteristics.

The enemy submarine used in our model occurs in two variations--one which is termed a "noisy" submarine, and an improved variation termed a "quiet" submarine. The "quiet" submarine is used as the enemy submarine in our basic problem. This is a nuclear submarine with noise characteristics about equal to those of our basic barrier submarine configuration, and its weapon system is the equivalent of that given to our basic submarine.

The "noisy" enemy submarine is used in one of the sensitivity test variations of our basic problem. This is a nuclear-powered submarine, but one that has decidely inferior self-noise and radiated-noise characteristics as compared with the basic barrier submarine configuration. Its weapon system is the same as that of the "quiet" submarine.

The same type of performance characteristics inputs are provided for each type of enemy submarine as for the barrier submarine.

Tactical Assumptions.

Various tactical assumptions must be made and provided as inputs to the computer-run tactical sub-model. The bulk of these tactical decisions were derived from actual tactical doctrine and hence are classified in nature.

Several basic tactical assumptions can be described, however:

(1) For problem purposes the enemy submarine is assumed to travel at a constant speed and on a course normal to the front of the barrier, until engagement takes place with the barrier submarine.

(2) It is further assumed that the enemy submarines transit singly, and arrive at the barrier at random intervals in time and with a uniform frequency distribution along the barrier front.

(3) At the beginning of each problem, each barrier submarine is patrolling about the approximate center of its area at some prescribed "secure" speed. This speed will be determined by the submarine configuration and by the sound conditions being used in the problem.

With the necessary limiting conditions and input data for our problem described, we are now ready to exercise our model to produce the output data in the form that we shall require for the comparison and selection of our alternatives, which are the four submarine configurations; i.e., (1) the basic nuclear-powered submarine, (2) the basic submarine plus the improved sonar alteration, (3) the basic submarine plus improved noise characteristics alteration, (4) the basic submarine plus an improved torpedo weapons system alteration.

The first step in the development of our problem output data is the generation of our production, or effectiveness, function.

The Effectiveness Function.

We shall produce this effectiveness function, first, for what we shall describe as our standard problem conditions, i.e., the quiet enemy submarine, average sonar conditions, and with no time "lost" by the U.S. submarines in proceeding to their barrier positions. The data for the effectiveness function is actually generated using the computer tactical sub-model described on page 10.

Using the computer-developed data, effectiveness functions are next constructed for each of the four alternative submarine configurations being compared. A set of curves displaying the effectiveness functions for the basic set of problem conditions is shown as Figure 4-2. These curves are presented with effectiveness (PK) shown on the vertical scale and numbers of submarines in the barrier shown on the horizontal scale. The information thus developed is classified so that actual numerical values cannot be shown; however our curves, as presented, provide a good basis for relative comparison from which important general characteristics are easily discerned.

It will be noted that each of the four effectiveness curves of Figure 4-2 show decreasing marginal return characteristics. It is also evident that all of the three proposed submarine alterations are more effective than the unimproved basic submarine, and that the improved torpedo system is markedly more effective than any of the other three alternative choices.

These curves, of course, were developed without reference to the costs of the various systems. Our next step is to combine the

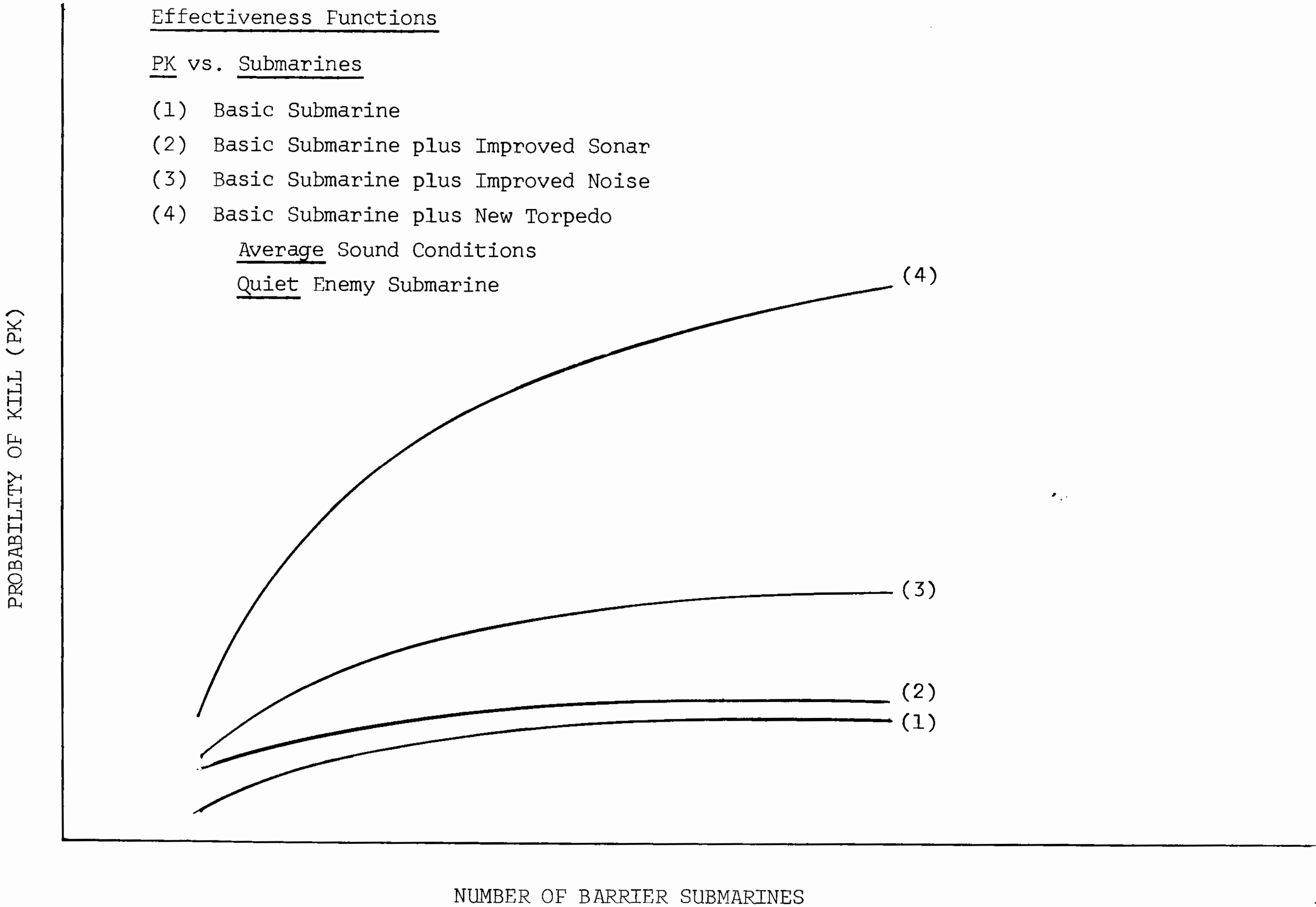

Effectiveness Functions
PK vs. Submarines
(1) Basic Submarine
(2) Basic Submarine plus Improved Sonar
(3) Basic Submarine plus Improved Noise
(4) Basic Submarine plus New Torpedo
Average Sound Conditions
Quiet Enemy Submarine
(4)
(3)
(2)
(1)
PROBABILITY OF KILL (PK)
NUMBER OF BARRIER SUBMARINES

FIGURE 4-2

cost functions that we developed in Chapter Three, Figure 3-1, with the effectiveness functions shown in Figure 4-2, to produce a relationship between total systems cost and effectiveness.

Cost-Effectiveness Curves; Standard Conditions.

These curves are shown in Figure 4-3. As mentioned previously, this type of curve provides us with our basis for selection from among the four alternatives presented for comparison.

Applying our criterion for comparison described in Chapter One, i.e., that alternative which produces the maximum effectiveness (PK) for the least total systems cost, it is clear from Figure 4-3 that the improved torpedo alteration, curve no. 4, is the most economically efficient system of the four alternatives. It should be noted, also, that applying our criterion in its other form; i.e., that alternative which produces the highest level of effectiveness (PK) for a given value of total systems cost, would give us the same result.

It will be noted also that the improved sonar alteration, curve no. 2, displays a relationship that appears extremely sensitive to a variation in total cost. An increase in the total systems cost of the improved sonar alteration in the amount shown by interval "A" in Figure 4-3, for example, would shift the entire curve no. 2 upward to the position shown by the dotted line. In this position the improved sonar alteration, curve no. 2, now enjoys a much less significant cost-effective advantage over the basic submarine, curve no. 1.

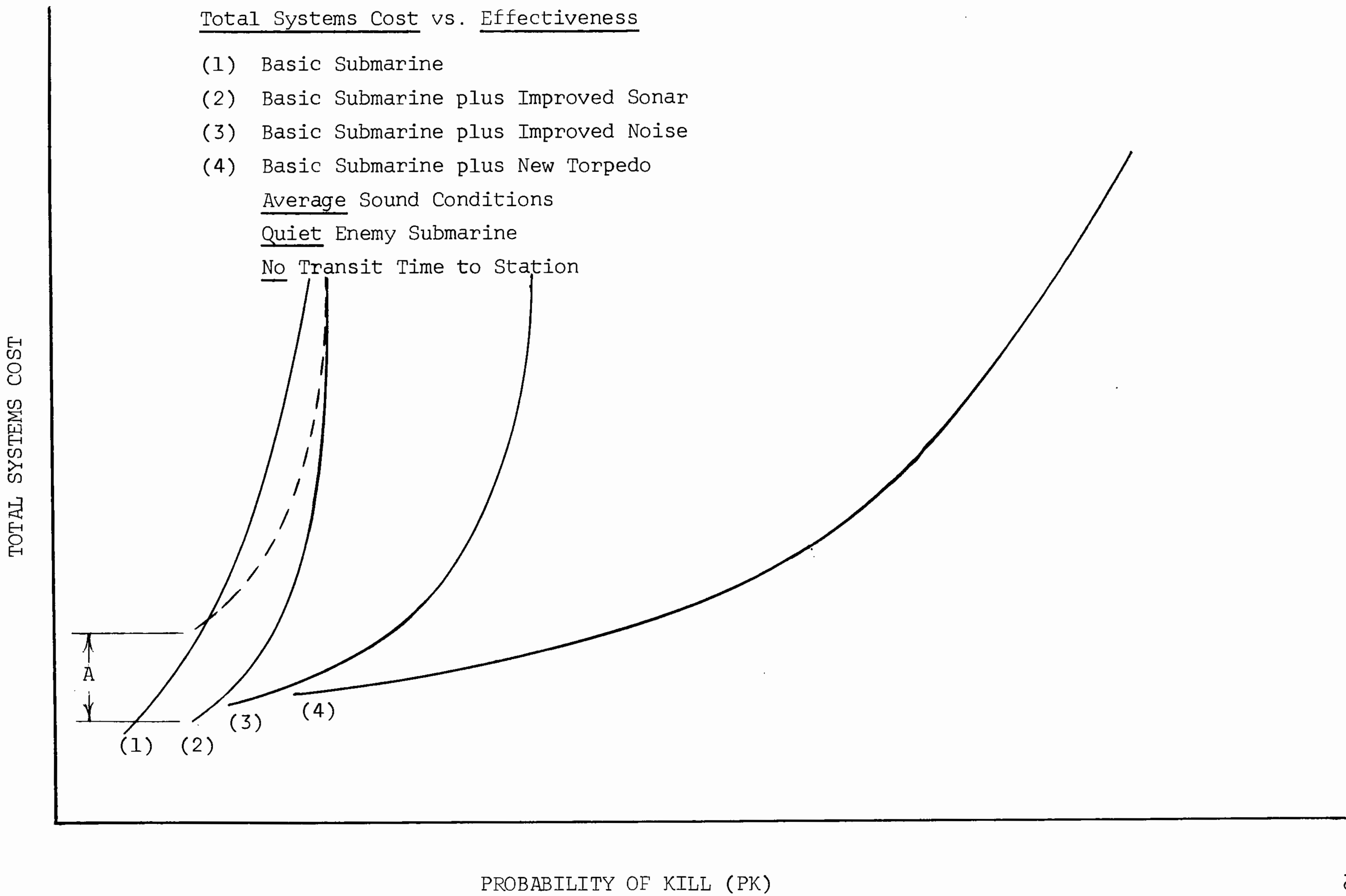

Total Systems Cost vs. Effectiveness
(1) Basic Submarine
(2) Basic Submarine plus Improved Sonar
(3) Basic Submarine plus Improved Noise
(4) Basic Submarine plus New Torpedo
Average Sound Conditions
Quiet Enemy Submarine
No Transit Time to Station
A
(1) (2) (3) (4)
TOTAL SYSTEMS COST
PROBABILITY OF KILL (PK)

FIGURE 4-3

This set of curves also provides a good basis for demonstrating the fallacy of using a ratio of cost to effectiveness as a criterion for selection. In a recent study conducted under the auspices of Naval Ship Systems Command, the criterion used for selection was the ratio of incremental increase in cost to the incremental increase in effectiveness per system unit, referred to a basic military system. To demonstrate this criterion we shall apply it to the lower left-hand points of all curves in Figure 4-3. Since these points represent the total-cost vs. effectiveness values for equal numbers of system units (submarines), the results will be in proportion to those calculated per system unit (per submarine).

We shall use curve no. 1 as our basic reference system in this instance. Referring to the increase in both total cost and PK values for curve no. 2 over curve no. 1 as a base index of 1, we find that Δ Cost/Δ PK $= \frac{1}{1} = 1$, for curve no 2 referred to curve no. 1; that Δ Cost/Δ PK $\cong \frac{3}{1.4} \cong 2.1$ for curve no. 3 referred to curve no. 1; and Δ Cost/Δ PK $\cong \frac{12}{2.7} \cong 4.5$ for curve no. 4 referred to curve no. 1.

Applying this cost/effectiveness ratio criterion then, would result in curve no. 2 being selected as the most efficient, and curve no. 4 being considered as the least efficient of the alternatives!

The relation of marginal costs $\left(\frac{\partial \text{ Cost}}{\partial \text{ PK}}\right)$ to PK for each of our alternative systems is displayed in Figure 4-4. These curves were derived from the total cost curves of Figure 4-3. They show the incremental increase in the total system cost for an additional

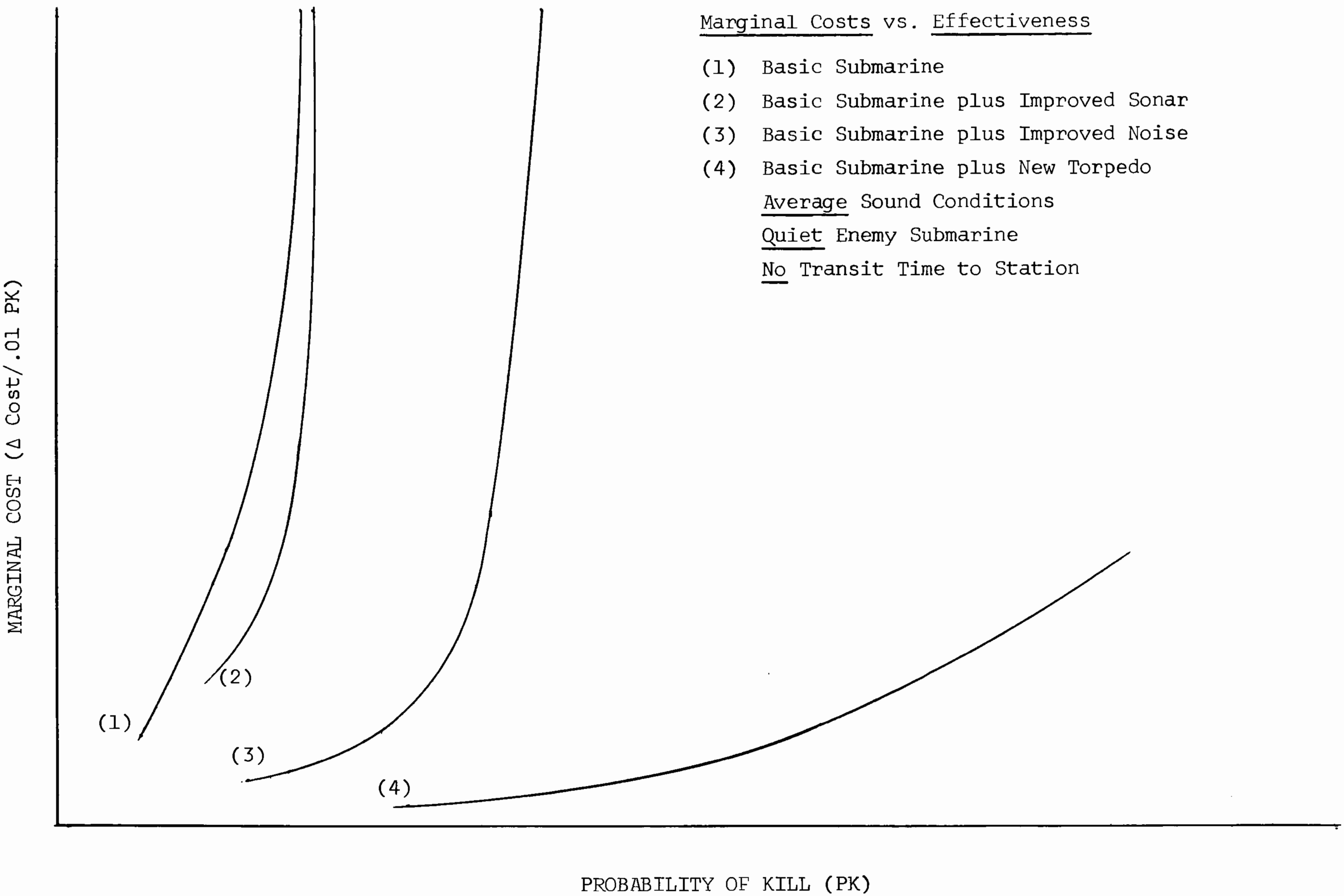

Marginal Costs vs. Effectiveness
(1) Basic Submarine
(2) Basic Submarine plus Improved Sonar
(3) Basic Submarine plus Improved Noise
(4) Basic Submarine plus New Torpedo
Average Sound Conditions
Quiet Enemy Submarine
No Transit Time to Station
MARGINAL COST (Δ Cost/.01 PK)
(1)
(2)
(3)
(4)
PROBABILITY OF KILL (PK)

FIGURE 4-4

unit of effectiveness (.01 PK) gained. Once a particular system has been selected, using Figure 4-3, then the marginal cost curves for that system can indicate to the decision-maker that level of effectiveness of operation of his force at which he will be getting the most return (in effectiveness) for the additional resource dollar expended.

Cost-Effectiveness Curves: Combinations of Alternatives; Standard Conditions (Figure 4-5).

Figure 4-5 shows the cost-effectiveness relationships for various combinations of the four alternative systems. The same standard problem conditions apply as in Figure 4-3.

The following conclusions can be drawn from these curves:

(1) The combination of the improved torpedo alteration and either or both of the other two alterations will result in a more cost-effective system than the improved torpedo system, alone.

(2) Curves nos. 2 and 3 show an interesting relationship, in that their relative positions are reversed from what one might be led to expect in examining Figure 4-3. Figure 4-5 shows that the improved torpedo plus improved sonar system, curve no. 3, is decidedly superior to the improved torpedo plus noise improvement system, curve no. 2; in Figure 4-3, however, the noise improvement shows up as considerably better than the sonar improvement system. This apparent paradox can be explained by the fact that the relative superiority of the noise improvement system, Figure 4-3, is due primarily to the advantage that low radiated noise gives

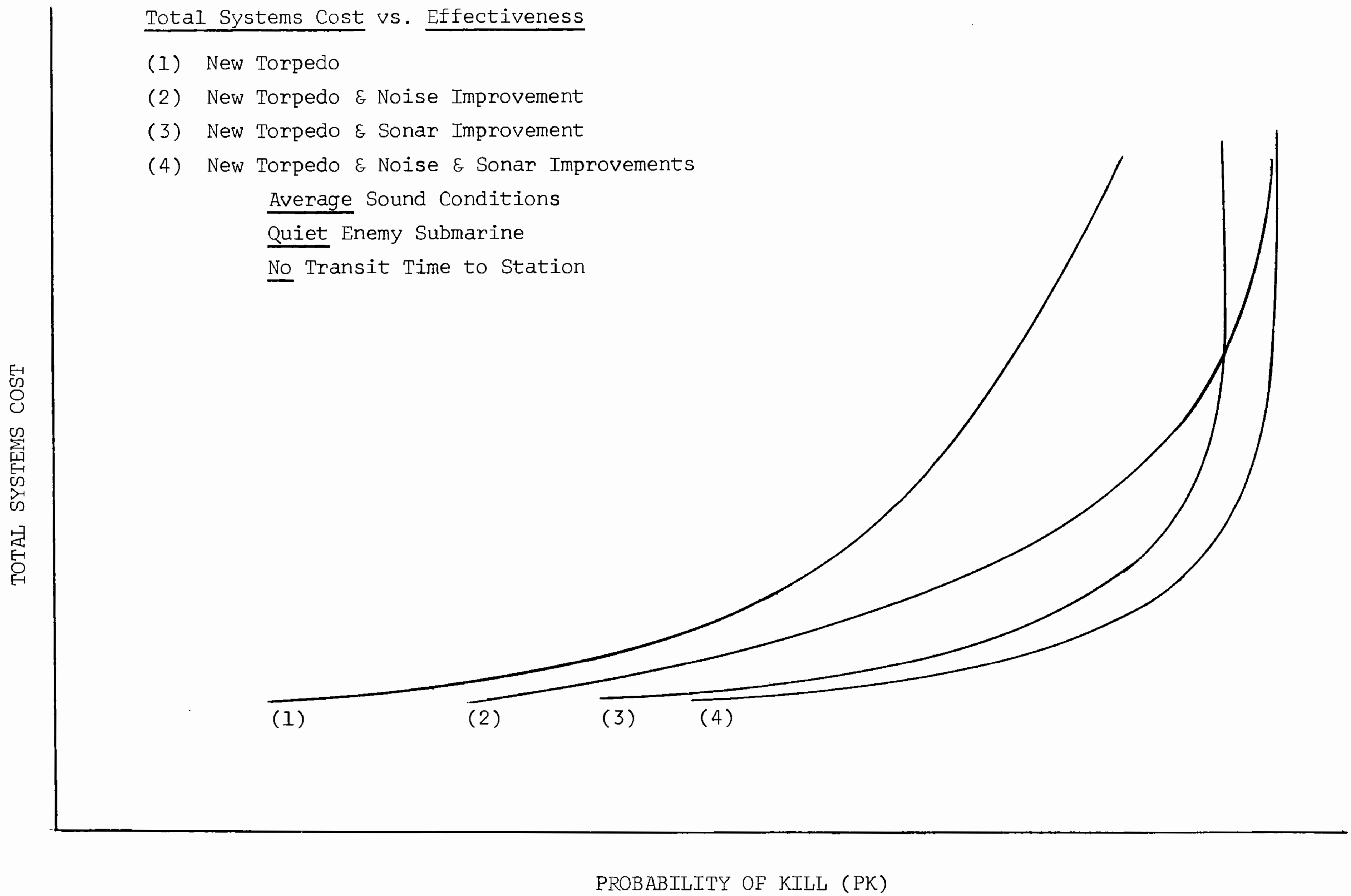

Total Systems Cost vs. Effectiveness
(1) New Torpedo
(2) New Torpedo & Noise Improvement
(3) New Torpedo & Sonar Improvement
(4) New Torpedo & Noise & Sonar Improvements
Average Sound Conditions
Quiet Enemy Submarine
No Transit Time to Station
(1)
(2)
(3)
(4)
TOTAL SYSTEMS COST
PROBABILITY OF KILL (PK)

FIGURE 4-5

to the barrier submarine over the enemy when the tactical engagement takes place at relatively close quarters. When the improved longer-range torpedo is installed, however, the engagements and and kills take place at a much longer range and the effect of the low radiated noise on the problem outcome becomes greatly diminished.

(3) Curve no. 4 appears extremely cost-sensitive when compared with curve no. 3, since a fairly small increase in total systems cost of the improved noise alteration will push the entire curve no. 4 upwards to the point where it will no longer be cost-effective with respect to curve no. 3, except at the extremely high range of effectiveness.

(4) It will be noted that curve no. 2 becomes more cost-effective than curve no. 3 at the higher end of the effectiveness PK scale. This point could be on interest to the decision-maker if he were planning on operating submarines in the type of high-density barrier operations under which a high level of effectiveness would be expected.

(5) The marginal cost curves, Figure 4-6, show that all of the combination systems, curves nos. 2, 3, and 4 show a much broader range of efficient operation than does the improved torpedo system considered alone, curve no. 1.

<u>Cost-Effective Comparisons - Sensitivity Test Number One</u> (Figure 4-7).

In this sensitivity test the standard problem conditions are altered by increasing both the radiated noise and self-noise level of the enemy submarine. This change in characteristics will result

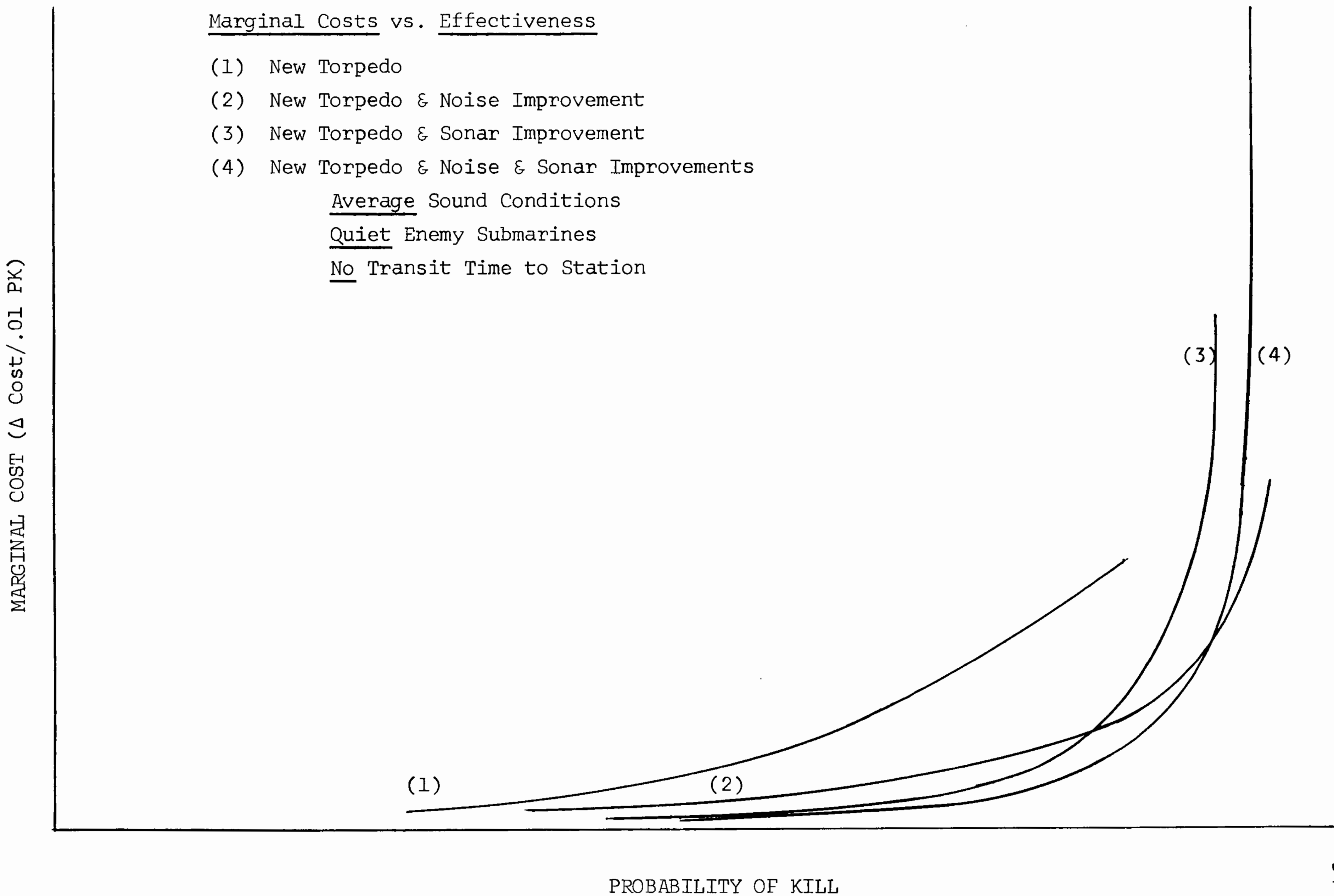

Marginal Costs vs. Effectiveness
(1) New Torpedo
(2) New Torpedo & Noise Improvement
(3) New Torpedo & Sonar Improvement
(4) New Torpedo & Noise & Sonar Improvements
Average Sound Conditions
Quiet Enemy Submarines
No Transit Time to Station
(1)
(2)
(3)
(4)
MARGINAL COST (Δ Cost/.01 PK)
PROBABILITY OF KILL

FIGURE 4-6

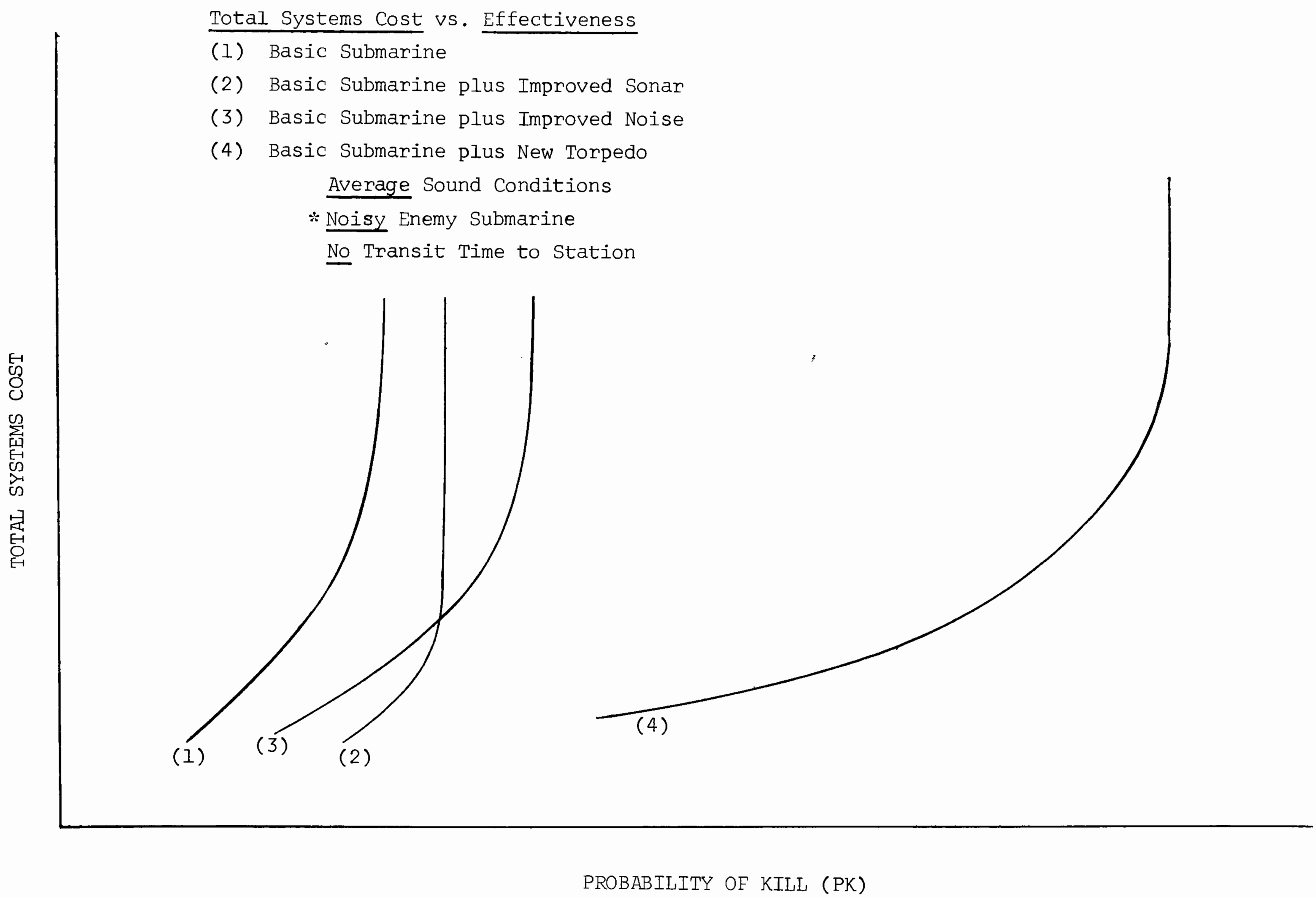

Total Systems Cost vs. Effectiveness
(1) Basic Submarine
(2) Basic Submarine plus Improved Sonar
(3) Basic Submarine plus Improved Noise
(4) Basic Submarine plus New Torpedo
Average Sound Conditions
* Noisy Enemy Submarine
No Transit Time to Station
TOTAL SYSTEMS COST
(1)
(3)
(2)
(4)
PROBABILITY OF KILL (PK)

FIGURE 4-7

in a reduced sonar detection capability on the part of the enemy; it will also result in an increased probability of the enemy being detected by the barrier submarine.

Comparing the results of our sensitivity test, Figure 4-7, with those produced under our standard set of problem conditions, Figure 4-3, reveals several areas in which significant variation is evident:

(1) Curve no. 4, the improved torpedo alteration, shows generally increased cost-effectiveness, particularly in the lower range of its effectiveness. It remains clearly the superior choice on a cost-effectiveness basis.

(2) Curve no. 3, the improved noise alteration shows only a slight increase in its cost-effective position. This is because the effect of the low radiated noise provided by this alteration is largely lost on the enemy submarine who has become relatively "deaf" because of his own high self-noise level.

(3) Curve no. 2, the sonar improvement alteration, shows increased over-all cost-effectiveness. This is due to the increased range of sonar detection made possible by the increased radiated noise-level of the "noisy" enemy submarine.

(4) In comparing curves no. 2 and 3 in Figure 4-7, no. 3 appears to provide the mose desirable overall characteristics. Curve no. 2 might prove interesting to the decision-maker concerned with the lower ranges of effectiveness only, but curve no. 3 shows a greater potential for expansion, and is clearly superior to 2 as the nature of the enemy threat improves, as shown in Figure 4-3.

Cost-Effective Comparisons - Sensitivity Test Number Two (Figure 4-8).

For this sensitivity test the basic mission scenario is changed so that the submarine barrier is now located at a significant distance from the port at which the barrier submarines are based. This has the effect, over an extended period of time, of requiring a larger total number of submarines to support a given number continuously maintained on the barrier, since a certain proportion of the submarines must always be involved in traveling to and from the barrier at any given instant in time. The result of this requirement for an increased number of submarines is, of course, that the total cost associated with a given level of effectiveness will be increased directly in proportion to the additional number of submarines required. In the case of the noise improvement system, however, the increase in total cost will be less than that for the other alternative systems. This is true because the reduction in radiated noise-level associated with the noise improvement program will allow the submarines to travel to and from the barrier at a higher speed and still enjoy the same degree of security from detection by enemy submarines. This higher speed means less travel time involved, which is directly translated into fewer submarines required to support the barrier and hence, lower relative costs.

Figure 4-8 shows the results of this sensitivity test. It will be noted that in comparison with Figure 4-3, curves nos. 1, 2, and 4 have all shifted upwards (become less cost-effective) due to the increased total costs. Curve no. 3, the noise improvement alteration, has shifted upwards, also, but to a lesser extent than

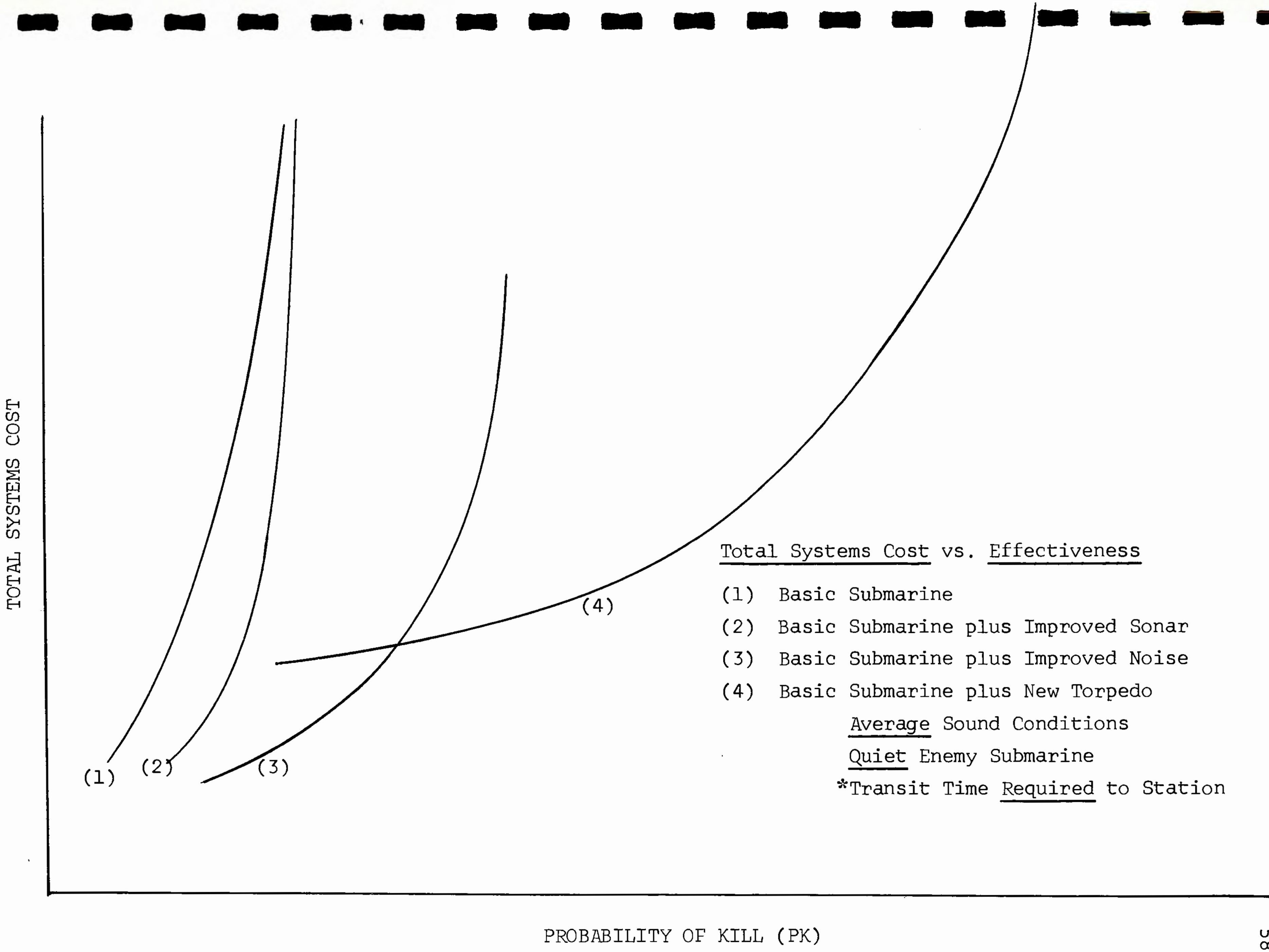

TOTAL SYSTEMS COST
PROBABILITY OF KILL (PK)
(1)
(2)
(3)
(4)
Total Systems Cost vs. Effectiveness
(1) Basic Submarine
(2) Basic Submarine plus Improved Sonar
(3) Basic Submarine plus Improved Noise
(4) Basic Submarine plus New Torpedo
Average Sound Conditions
Quiet Enemy Submarine
*Transit Time Required to Station

FIGURE 4-8

the others, causing it to become even more cost-effective in comparison to curves nos. 1 and 2, and producing an area in which it even becomes competitive with the improved torpedo alteration, curve no. 4.

This effect could have a significant impact on other of our problem cases. In the case of Figure 4-5, for example, the addition of the effect of the travel time to the barrier would shift the new torpedo plus noise improvement, curve no. 2, relative to the others so that it could easily become competitive with curve no. 3, the new torpedo plus sonar improvement curve.

Cost-Effective Comparisons - Sensitivity Test Number Three (Figure 4-9).

In this test the standard set of conditions are varied by an improvement in the environmental conditions, namely the sea-state. This will result in improved detection capability for both the barrier submarines and the enemy submarines. The effect of this variation proves to be essentially uninteresting. Comparison with Figure 4-3 shows that all of the alternatives, curves nos. 1, 2, 3, and 4 increase their cost-effectives -- but all maintain their approximate relative positions.

An important aspect of our system of comparisons should be noted at this point. We have been interested strictly in the selection of one alternative as opposed to another. We are not concerned with the quite different problem of obtaining an efficient "mix" of the competing alternatives. Such a "mix" of systems, within the context of our problem, would imply that one submarine might be purposely outfitted with an improved sonar but inferior torpedo system and another submarine with improved torpedo but inferior sonar. This type of a solution is not applicable to the category of problem that we have under consideration for several reasons:

(1) Under the basic problem assumptions, the barrier submarines operate independently of one another. Under such conditions, each submarine functions as a self-contained unit and has only its own weapons and sensor system with which to protect itself and to detect, track, and kill the enemy. It is therefore necessary that each submarine be outfitted with the most economically efficient system that can be provided. This requirement can be considered to be in the nature of a technological constraint when considered in the context of our production firm analogy of Chapter One.

(2) The second reason is mathematical in nature, and pertains to the relationship that exists between the production functions of the various alternatives. In order that the basic conditions obtain whereby an efficient "mix" of any two systems can be determined, it is necessary that their basic effectiveness (production) functions be additive in nature. Considering Figure 4-2, this would imply that, for example, a .50-.50 mix of the noise improvement alteration, curve no. 3, and the torpedo improvement alteration, curve no. 4, would result in a hybrid effectiveness function that would show characteristics of curve no. 3 for the first half of its range and characteristics of curve no. 4 for the last half, or vice-versa. A moment's consideration of the

problem, however, will lead us to conclude, intuitively, that the effectiveness function of the "mixed" barrier will be neither of the above two results, but a smooth-form function lying between curves nos. 3 and 4. The fact that the basic relationships involved are not additive, is further strongly suggested by the results previously noted in the combined systems curves of Figure 4-5. In this figure the noise improvement alteration and the sonar improvement alteration reversed their relative positions when combined with the basic torpedo alteration. This is just the opposite of results that would have been predicted if the relationships were, in fact, additive.

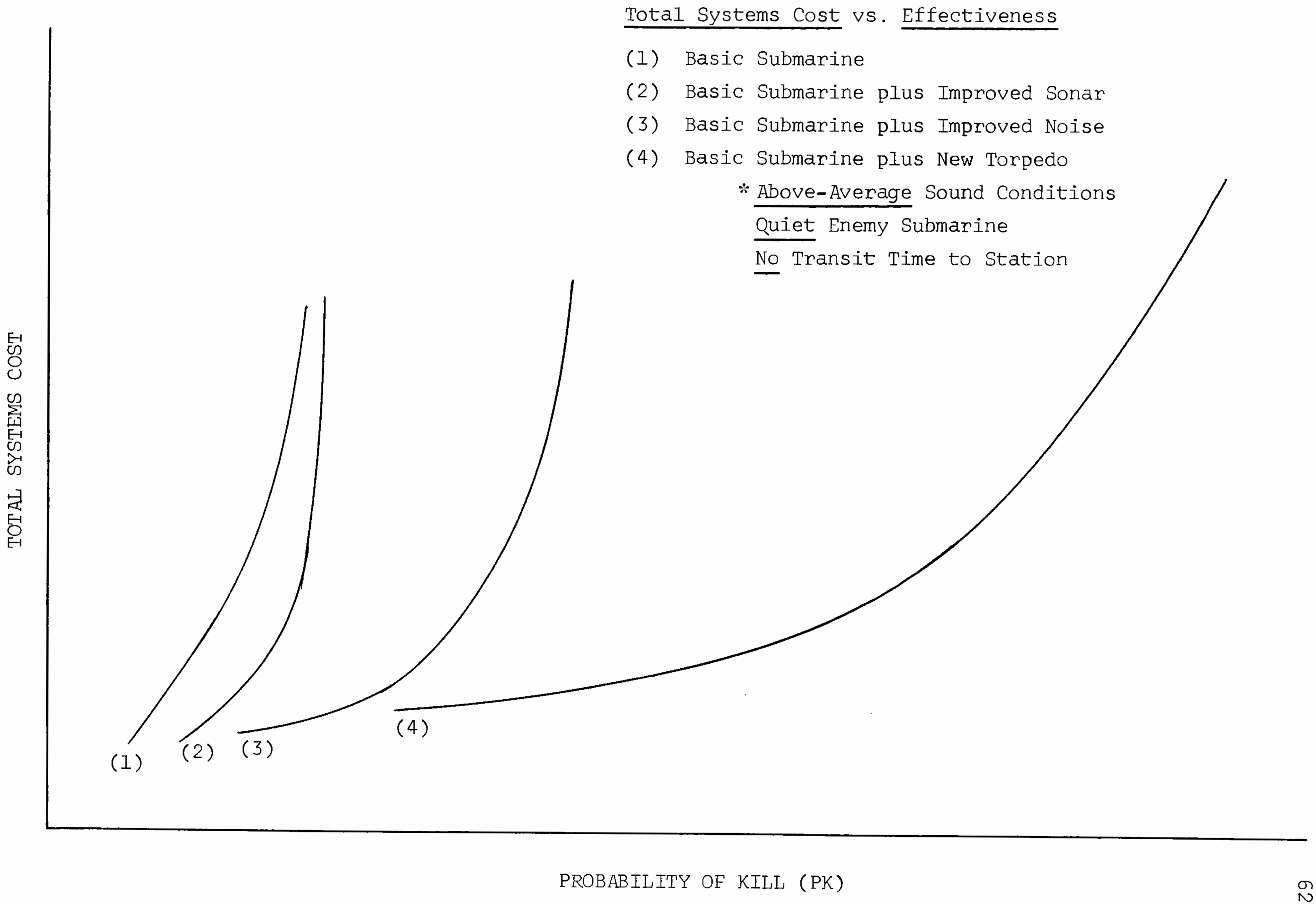

Total Systems Cost vs. Effectiveness
(1) Basic Submarine
(2) Basic Submarine plus Improved Sonar
(3) Basic Submarine plus Improved Noise
(4) Basic Submarine plus New Torpedo
* Above-Average Sound Conditions
Quiet Enemy Submarine
No Transit Time to Station
TOTAL SYSTEMS COST
(1)
(2)
(3)
(4)
PROBABILITY OF KILL (PK)

FIGURE 4-9

Summary of Results.

The results that we have obtained in the exercise of our methodology present to the decision-maker the necessary information from which to draw a number of meaningful observations with respect to the four alternatives being compared:

(1) The improved torpedo alteration is clearly the superior choice, on a cost-effective basis, of the four alternatives presented for comparison within the specific military mission considered, i.e., the destruction of enemy submarines through the use of an anti-submarine, submarine barrier. The improved torpedo alteration maintains a clear advantage over the other alternatives throughout nearly the entire range of parameter variations tested.

For all ranges of effectiveness (PK) the improved torpedo system will provide the desired probability of kill (PK) for the least total cost, or least total resource expenditure for the specified mission, with a single exception. That exception has a narrow range of application and is illustrated by Sensitivity Test Number Three (Figure 4-8), which considers the variation in results caused by a requirement for transit time to and from the barrier. In this case, the improved noise alteration (curve no. 3) overtakes the new torpedo alteration (curve no. 4), in the lower segment of its effectiveness range. This small area of advantage, however, should prove of less significance than the fact that curve no. 4 offers opportunity for expansion at low and and fairly constant marginal costs over an extended range of effectiveness levels.

(2) The improved torpedo alteration can achieve increased cost-effectiveness by being employed in combination with either or both of the competing alterations, Figure 4-5.

At this point, the decision-maker should proceed with caution in interpreting the results, however. Figure 4-5 clearly shows that the improved torpedo in combination with the improved sonar alteration, curve no. 2, is more efficient than the improved torpedo in combination with the noise improvement alteration, curve no. 3, for the "standard" set of problem conditions. Based on the results noted in Figure 4-8, however, we would expect that any system incorporating the noise improvement alteration would show considerably increased cost-effectiveness under conditions in which transit time were required for the submarines proceeding to and from station. For this reason the decision-maker should conduct a sensitivity-test with transit-time as a variable before arriving at any definite conclusions as to the relative cost-effective positions of curves no. 2 and 3, in Figure 4-5.

(3) In the event that the decision-maker's area of consideration must be confined to a selection between the improved sonar alteration, and the improved noise alteration, then the selection is somewhat less clear than in the case presented by paragraph (1) above, since the relation between these two alterations shows a sensitivity to the variation of several of the basic problem parameters.

For example, if a "noisy" enemy submarine were postulated, as in Figure 4-7, then either the improved sonar alteration, curve no. 2, or the improved noise alteration, curve no. 3, could be selected depending on the range of effectiveness in which the decision-maker planned to operate the barrier submarines. The decision would become simpler, however, under conditions which required significant transit-time to the barrier stations. As Figure 4-8 shows, the noise improvement alteration, curve no. 3, can be expected to show an overall increased cost-effectiveness with respect to the sonar improvement alteration, curve no. 2. If, however, it were postulated that the enemy noise characteristics were inferior to those used in Figure 4-7, then the improved sonar curve could be expected to gain relative to the improved noise curve. In both cases additional sensitivity tests would be clearly indicated.

It is important, at this point, to note that the decision-maker would be well-advised not to make his final selection based on the results of our test problem, alone. This is so, due primarily to the fact that because of the need to narrow our area of investigation, we considered only <u>one</u> mission of the nuclear submarine in formulating our problem. That mission was, of course, the destruction of enemy submarines while operating in an anti-submarine barrier. There are, numerous other specific missions of both hot-war and cold-war nature, that nuclear submarines are capable of performing. Any selection of alternative ship-alterations should therefore be based on consideration of the competing alterations in the performance of the other pertinent mission areas. The methodology developed in this paper should provide a framework for the conduct of cost-effectiveness analysis of other missions, once the basic measure-of-effectiveness (MOE) have been determined for those missions.

With the results thus presented as to the performance of the alterations being compared in the various relevant mission areas, the decision-maker can select the most efficient system for each specific mission being considered, and from these "semi-final" selections make the final selection or selections of the various ship-alteration alternatives being compared.

Conclusions and Critique.

Based on the review of the results produced by our model, it can be fairly concluded that we have developed within this paper a methodology that has a direct and practical application to the problem that was presented at the outset of our study, namely, that of selecting the most economically efficient ship-alteration from a group of proposed alternatives. While the subject of broader utilization of our model was not addressed in our analysis, it nonetheless appears that our basic methodology has also a range of application to a much wider scope of problems, including other mission categories of submarines and extending to other ship-types as well.

The dimensions of the problem that we constructed for the exercise of our methodology were necessarily constrained by the scope and objectives of the study. As a result our model, as presently configured, requires modifications and extensions before it can be directly applied to a practical real-world version of our study problem. Some primary areas which require additional analysis and development are discussed below:

(1) The tactical sub-model was severely constrained by the assumptions made with regard to the tactics that the enemy submarine would use; e.g., that enemy submarine arrivals at the barrier would occur singly and would occur essentially as random independent events; that the enemy submarine would travel at a fixed course normal to the barrier front and at a fixed speed.

These limitations can be readily corrected by expanding the capabilities of the basic computer tactical sub-model to accommodate tactical situations in which enemy submarines can be made to operate in the various tactical options which are obviously open to them, e.g., simultaneous arrival in numbers greater than one, "saturation" type raids which concentrate a large number of enemy submarines on a single barrier submarine, etc. Such flexibility would allow for the evaluation of proposed equipment and weapon systems in a realistic tactical environment more closely comparable to the real-war situation in which such systems may actually be required to function.

(2) Only one measure-of-effectiveness, the probability of the barrier submarine killing the enemy submarine (PK), was used in our model. In actuality, any model purporting to represent realistically a two-sided engagement must also take into account the probability of the enemy submarine killing the barrier submarine. Our tactical sub-model thus should be capable of producing output in terms of both probability-of-kills. While the enemy's probability-of-kill does not appear to be directly amenable to the type of economic analysis that we applied to the barrier probability-of-kill (PK) in our model, it can nevertheless be employed by the upper-level decision-maker as another one of the judgement inputs he uses in arriving at his final selection. The form which appears most useful is the combining of the two probability-of-kills into a ratio, termed an "exchange ratio".

This exchange-ratio represents the ratio of barrier submarines lost per enemy submarine destroyed. Such a measurement value is obviously of interest to the decision-maker since, when applied over a period of extended engagement, it provides a direct measure of the ability of the barrier submarine force to support a sustained operation.

(3) The range of sensitivity-testing that should be applied to problem results is undoubtedly considerably greater than that used for purposes of illustration in our paper. The scope of sensitivity testing should be sufficient to provide the decision-maker with a reasonably complete picture of the performance of the alternatives under as broad a range of relevant circumstances as possible. A number of areas appear particularly fruitful for additonal testing of this nature:

(a) Sound propagation conditions are known to vary widely throughout the world. Since sound propagation directly affects the ability of one submarine to detect another, variations would undoubtedly have a critical impact on the results obtained. For this reason sensitivity tests should be applied, varying the sound propagation parameters to correspond with those areas of the world in which the submarine is likely to operate.

(b) Sensitivity tests should be applied to the full range of possible enemy submarine configurations and characteristics that are necessary to describe the enemy's potential threat during the time frame being considered.

(c) The characteristics of the basic U.S. submarine should also be varied. While in our paper we confined our attention to the consideration of a single type of U.S. submarine, a full-range sensitivity test should include sufficient variation to encompass the major classes of U.S. submarines, present and future, to which the proposed alterations are considered applicable.

(4) As noted previously, the model used in this study considers the U.S. submarine operating in but a single mission and measures the performance of the various alterations in that mission environment only. In order to obtain a comprehensive view of the overall effectiveness of each individual alteration, its performance in all possible mission assignments should be evaluated. While the methodology developed in this paper should provide a satisfactory framework for cost-effective evaluations in the other submarine missions, further analytical work will be required to devise some acceptable system for weighting the relative worth of the various missions for purposes of comparisons. A related problem is that of evaluating the worth of alterations that do not improve specific performance characteristics of the submarine, e.g., improved crew's berthing or laundry facilities. A method is needed that will somehow relate the advantages that these types of alterations produce to the submarine's ability to perform its missions.

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